

# **Advanced Composites Initiative: accelerating the design/development/manufacturing life cycle for advanced composite materials for civil aviation vehicles\***

**--- Draft Proposal for Preliminary Planning Discussions ---**

**Updated January, 2012**

**Abstract:** After four decades of intense research and product development, great advances in the application of composite materials for primary structure of aerospace vehicles have been achieved. For example, the B787 is just over 50% composites by structural weight and exploits the tailorability of composite materials to achieve a highly efficient new wing design. However, the time and cost of new product development remains unacceptably high in a fast paced product innovation-based global economy. This deficiency also prohibits new entrepreneurial entries into the marketplace and constrains the trade-space for new product innovation. Recent advancements in modeling and simulation capability, when coupled to advanced manufacturing methods, represents a fertile environment to develop an integrated, end-to-end, robust methodology that will span from selection of new materials to product design/development, and certification. The broad outline for an initiative that embodies this integrated methodology is described herein. Once successful, this new initiative has the potential to revolutionize the development of innovative products that fully exploit the dramatic strength, stiffness, and durability properties of advanced composites relative to conventional metallic materials, as well as enable system-level optimization of multifunctional designs - dramatically lowering weight for enhanced fuel efficiencies.

**Introduction:** U.S. leadership in aviation has been severely challenged by Europe and is surely to be challenged by new and emerging economic powers such as China, Brazil, and others.<sup>1</sup> One of the areas where the U.S. is a clear world leader is Composite Materials and their utilization in aircraft. The Boeing 787, the Lockheed F-22 and the Northrop Grumman Global Hawk are the prime examples. Recently Airbus announced plans to introduce the A350 widebody aircraft as their answer to the Boeing 787 Dreamliner. With its introduction (expected in 2014) Europe's aircraft industry will achieve parity with the U.S. **This advancement illustrates the imperative to introduce innovative new products into the market-place on an accelerated timeframe.** To ensure that the U.S. maintain a global leadership position in this area, investment is needed so that the U.S. industry can more rapidly innovate and find ways to incorporate the technology into both new and existing products, and do so with greater confidence in a successful outcome.

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<sup>1</sup> For example, investments in European Framework programs and matching industry investment total 2B Euro's. There are also significant investments by individual countries such as Korea, Japan, Germany and France which are focused specifically on composites.

**Problem Statement:** While the electronics and automotive industries have incorporated advances in design and manufacturing technology to accelerate their product development cycle - in spite of increases in product complexity - the opposite trend had occurred for aerospace vehicles – as illustrated by figure 1. One component of this increase in development time is related to the present paradigm for incorporation of new materials. The time and cost presently expended to develop and transition a new material system from the research laboratory into a certified, manufactured product is quite large, often taking 10 to 20 years and costing hundreds of millions of dollars. This extended time gap between materials invention and transition to product innovation has been called the technology development “valley of death”. Because of this gap, the deployment of advanced composite materials, with superior properties to those of conventional metallic materials, into innovative new aerospace products is quite slow. Accelerating the time to deployment will enable U.S. industry to introduce lightweight, fuel-efficient aircraft into the fleet and will ensure U.S. leadership and economic vitality. The traditional paradigm of materials transition to product innovation is illustrated in Figure 2 for carbon fiber reinforced composites. This paradigm has been successfully used in all aircraft including the development of the “all composite” Boeing 787 (see figure 3). However, it must change to enable new product innovation consistent with the rapidly accelerating pace of 21<sup>st</sup> century innovation-driven economic development.

**Program Objective:** accelerate the timeline to bring innovative composite materials/structures products to market (**goal: 3 year design/development/certification cycle**).

Ultimately this advancement is expected to:

1. Accelerate the design, development, verification, and regulatory acceptance of advanced vehicle structures which will allow U.S. industry to bring new innovative products to market quicker and at reduced cost which in turn improves their competitiveness.
2. Dramatically improve predictive capabilities such that they can be used to in a way to decrease program cost and schedule risk caused by material, structural and manufacturing uncertainties associated with new technologies.
3. Increase design robustness (durability and damage tolerance) which leads to reduced structural weight and reduce life cycle costs. This enables new aircraft, spacecraft and other vehicles that are lighter, more efficient, and easier to maintain.
4. Increase the presently inadequate skill base of technologists, engineers, designers, and technicians having the ability to develop and ultimately to safely maintain composite structures.
5. Impact areas beyond aerospace including, but not limited to, the automobile and shipbuilding industries.

**Themes (R&D focus areas):** This objective can only be achieved by accelerating the on-going efforts in computational modeling and simulation - taking advantage of recent advances in our understanding of mechanics of composites and our rapidly maturing computational methods to predict material properties, to predict nonlinear response and complex stress states, to predict composite failure initiation and progression, and to simulate manufacturing processes; as well as the maturing of structural design tools that utilize advanced optimization schemes and probabilistic methods - and using them within an aggressive **systems integration** approach to create a revolutionary new paradigm for vehicle design, development, and certification. The elements of the new design paradigm that must be integrated include:

1. Exploit materials design-by-analysis computational methods to achieve rapid development of design allowables for emerging advanced materials (Goal: reduce materials design allowables coupon tests from 10s of thousands by an order of magnitude).
2. Validate structural design tools at multiple length scales to significantly reduce the number of developmental tests for structural certification (see figure 4 below).
3. Develop high production rate, near-net-shape, large-component manufacturing methods and the corresponding manufacturing computational simulation methodology to accelerate the pace of re-engineering current vehicle product lines by replacing metals with advanced carbon-fiber composites, hybrids, and emerging new material systems.
4. Streamline certification methods that ensure structural safety through quantified risk management approaches that rely on advanced modeling and simulation methods, including probabilistic design methods.
5. Demonstrate integration of computational methods for material design, structural design practice, and manufacturing into a synergistic virtual development environment (figure 5(c) below), including the integration of separate discipline design tools (e.g., electromagnetic environment effects) to optimize multifunctional structures for system performance

**Investment:** 50%-50% cost-sharing between NASA, FAA, and Industry (ROM estimate: ~\$50M per year for 5 years for NASA); this new initiative will significantly augment the current related research activities in NASA's Aeronautics portfolio and will require an increase to the current NASA Aeronautics funding level. [Note: need FAA partnership to work certification issues to pave the way for acceptance of advanced design/development methods]

### **Building Partnerships and Stakeholder Advocacy:**

**Industry:** NASA has already implemented several mechanisms to engage industry to improve the relevance and impact of its research programs. One key example is the new Aeronautics Industry Roundtable that includes diverse representation across the aeronautics field. It is likely that this proposed technology development program will require the establishment of a new public-private partnership to assure a fully successful outcome.

It is anticipated that there will be widespread industrial interest from across the country in the proposed new program. In addition to contributing to the development of new predictive methods, industry will play a key role in applying newly developed methods and tools in practical applications that will help demonstrate progress and guide the overall effort.

**Congress: 2011 Language in the FY11 House Authorization bill:**

The Administrator shall expand NASA's research program on composite materials used in aerospace applications to address:

- (1) Progressive damage analysis, aging, inspection techniques, and new manufacturing and repair techniques;
- (2) Ways to mitigate how the environment, operating fluids, and mechanical loads interact with composite materials over time.

**Administration: 2011 Executive Office of the President,**

President's Council of Advisors on Science and Technology (PCAST), report entitled "Report to the President on Ensuring Leadership in Advanced Manufacturing", June 2011, calls for a partnership between government, industry, and academia to identify the most pressing challenges and transformative opportunities to improve the technologies, processes and products across multiple manufacturing industries. Key steps being taken by the federal government include:

- (1) Building domestic manufacturing capabilities in critical national security industries;
- (2) Reducing the time to develop and deploy advanced materials
- (3) Investing in next-generation robotics
- (4) Developing innovative energy-efficient manufacturing processes.

**Excerpt from report:** While the United States may not be able to compete in the long run to make goods for which low-wage unskilled labor is the key input, this need not be true for sophisticated manufacturing linked to products and processes derived from scientific discovery and technological innovation. There are three compelling reasons why we should strive to revitalize our leadership in manufacturing:

1. Manufacturing, based on new technologies including high-precision tools and advanced materials, provides the opportunity for high-quality, good-paying jobs for American workers;
2. A strong manufacturing sector that adapts to and develops new technologies is vital to ensure ongoing U.S. leadership in innovation, because of the synergies created by locating production processes and design processes near to each other; and
3. Domestic manufacturing capabilities using advanced technologies and techniques are vital to national security.

PCAST focuses in this report on advanced manufacturing, a family of activities that (a) depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or (b) make use of cutting edge materials and emerging capabilities enabled by the physical and biological sciences, for example nanotechnology, chemistry, and biology. This involves both new ways to manufacture existing products, and especially the manufacture of new products emerging from new advanced technologies. We believe that advanced manufacturing provides the path forward to revitalizing U.S. leadership in manufacturing, and will best support economic productivity and ongoing knowledge production and innovation in the Nation.

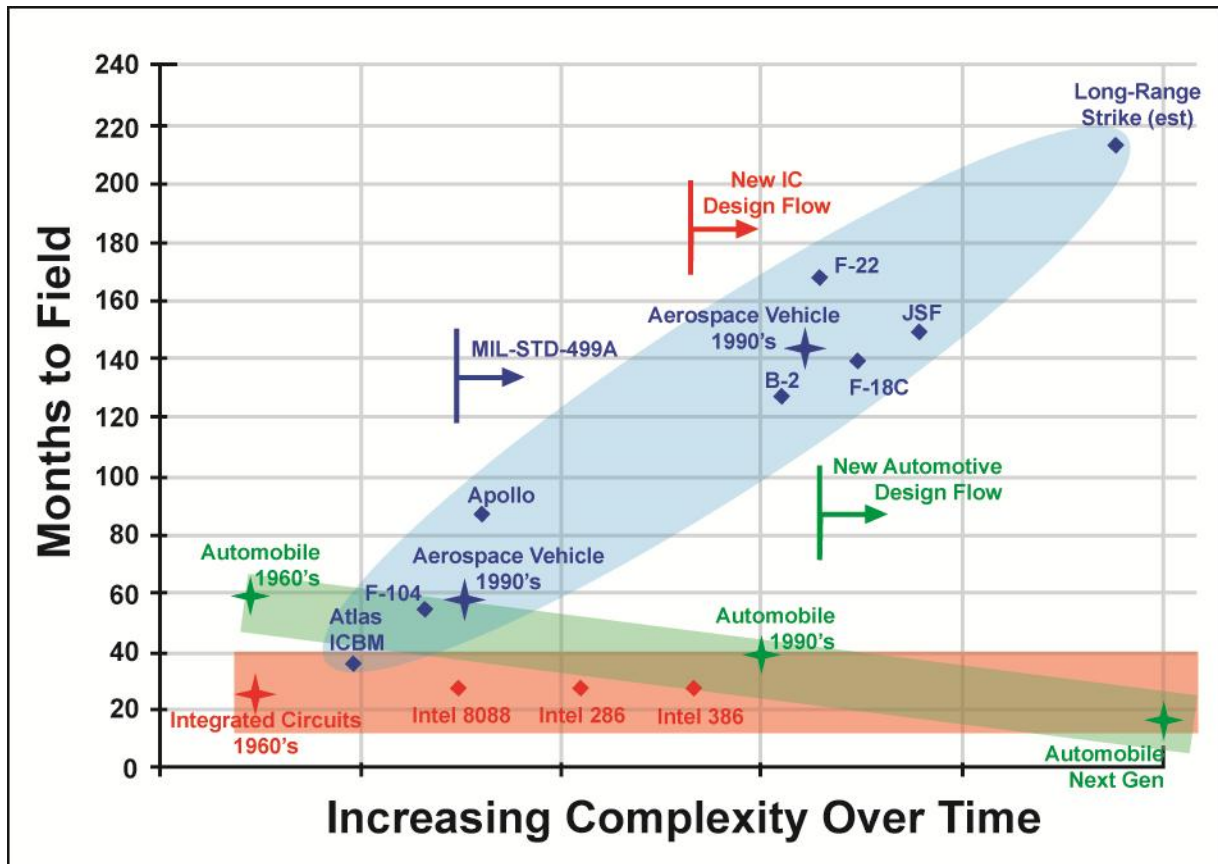


Figure 1 – Comparison of change in development time with system complexity for aerospace, electronics, and automotive systems (from “DARPA Adaptive Manufacturing Initiatives” presentation at 2011 Defense Manufacturing Conference)

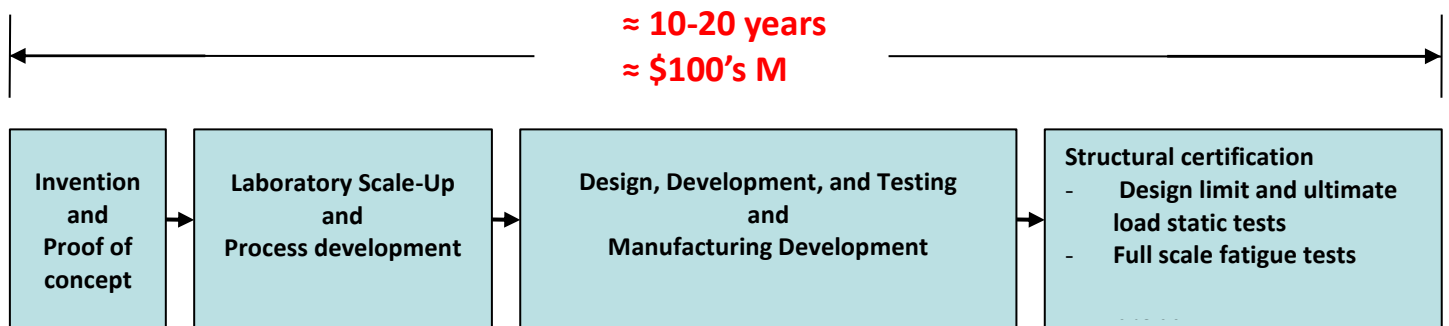


Figure 2. The traditional paradigm of materials transition to certified products.

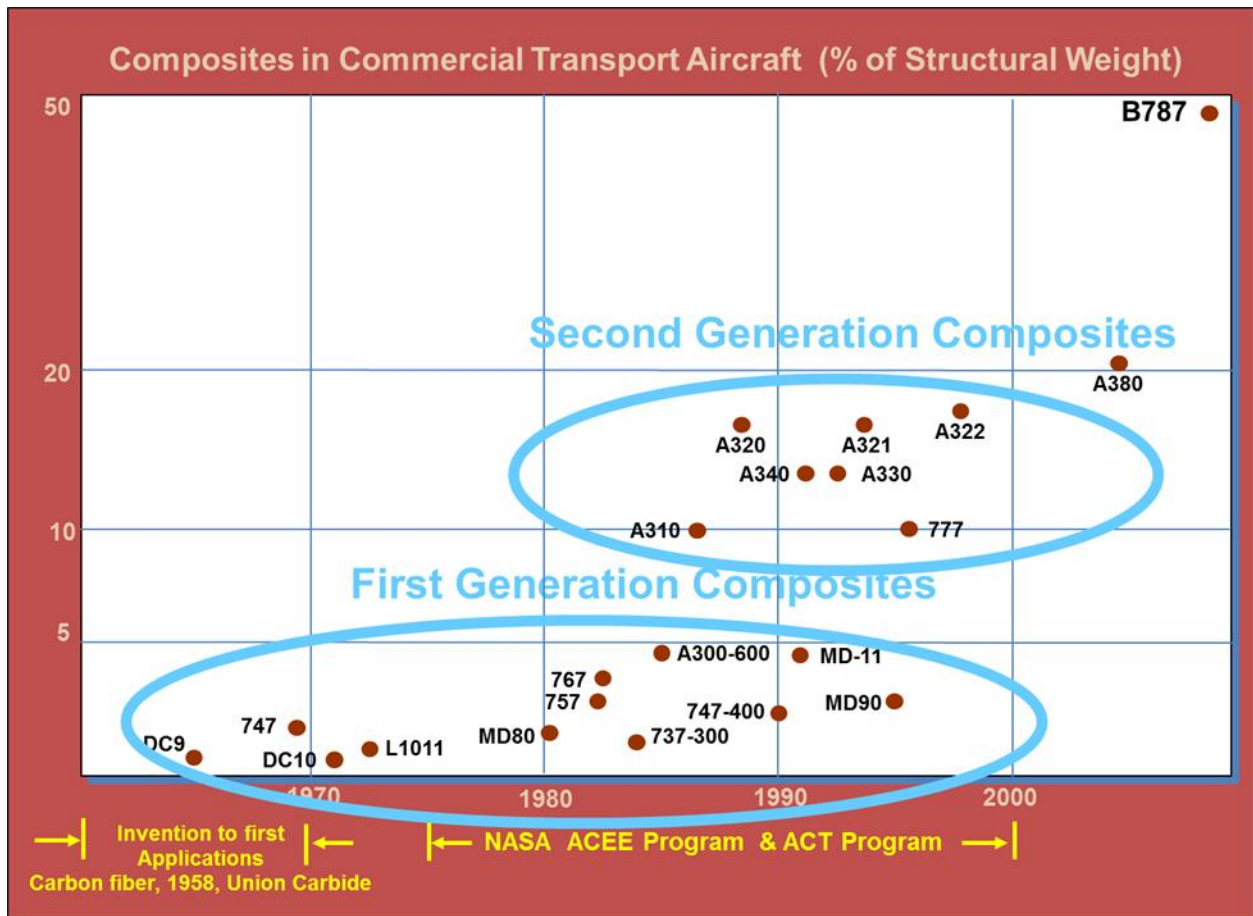
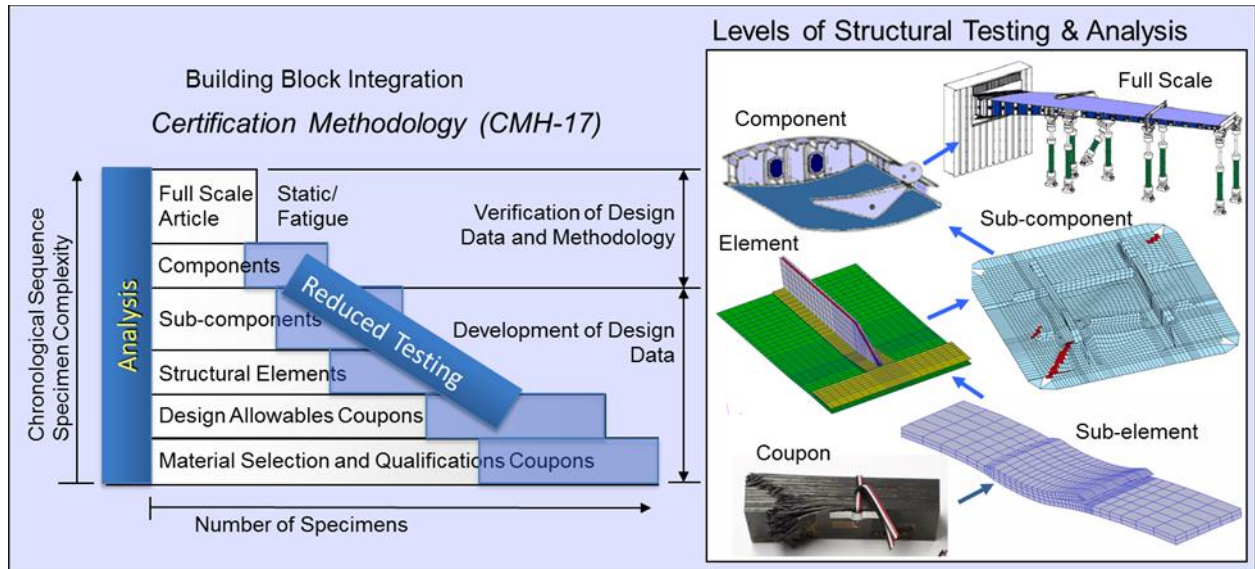
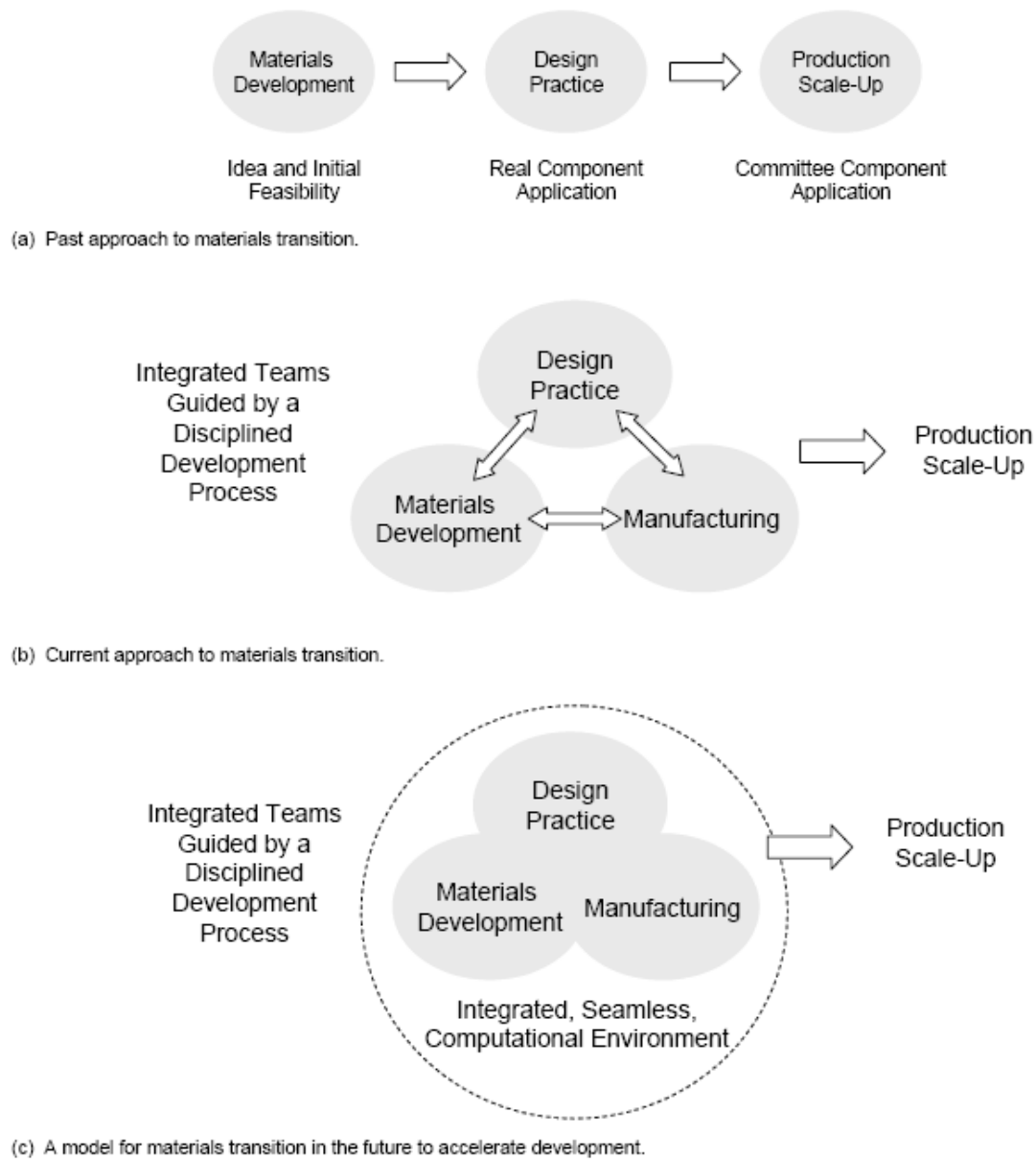


Figure 3. Evolution of Composite Materials into Primary Structure of Transport Aircraft



**Figure 4. Validated structural design tools at multiple scales will significantly reduce the number of developmental tests needed for structural certification**



**Figure 5. Integration of computational methods for material design, structural design practice, and manufacturing into a synergistic virtual development environment (from “Accelerating Technology Transition: Bridging the Valley of Death for Materials and Processes in Defense Systems”, Committee on Accelerating Technology Transition, National Research Council, 2004)**

## **Background**

### **The State-of-the-Art in Design and Analysis Methods for Composite Structure**

While significant improvements have occurred to structural design and analysis methodologies over the past two decades, the current standard practices used by the aerospace industry are still largely semi-empirical. Finite element methods and sophisticated computer codes are used routinely to calculate accurate stress, strain, and displacement fields for complex structures subjected to in-service, combined loads. Superior graphical interfaces have significantly improved pre- and post-processing of data files. Automated mesh generation, mesh refinement, and automated adaptive re-meshing have resulted in major efficiencies in model preparation time, analysis time, and accuracy of the numerical solutions. Post-processing algorithms and graphical interfaces have significantly improved the ability of the analyst to interpret the results of the stress analysis. However, the prediction of structural failure modes, ultimate strength, residual strength of damage-tolerant structure, and environmental durability and fatigue life has remained elusive for the structural engineer. A rigorous structural analysis suitable for predicting structural failure requires the prediction of high-fidelity local stresses and local stress gradients that can be used with physics-based failure criteria and damage models. The global/local analysis method is one method currently under development to predict structural failure. A rigorous global/local analysis method must also include a progressive damage analysis capability to determine the residual strength of the structure as damage propagates and the associated fatigue life. The progressive damage analysis method must have the capability to predict the initiation and growth of damage due to the anticipated structural loading conditions and vehicle service environment. At the present time, rigorous analysis methods for metallic structures are much more mature than are the corresponding methods for composite structures. This observation is primarily attributed to the fact that engineering fracture mechanics methods which predict fatigue crack growth and catastrophic failure (fracture) of metallic structures are in routine use throughout industry. In addition to the complexity of predicting damage initiation and growth in composite structure, nonlinear structural response characteristics such as buckling, post-buckling, and pressurized structural deformations cannot currently be predicted accurately. The analyses necessary to predict these nonlinear response characteristics must include the appropriate material properties for composite materials and the computational methods must account for material anisotropy. Physics-based, rigorous progressive damage analysis methods offer great potential to model failure modes accurately and to predict the residual strength of composite structures. However, these methods are not yet fully developed for aerospace vehicle applications. Most models do not have a complete representation of all failure modes, complex damage states, and combined stress states. Physics-based failure criteria are still primitive. Loading history dependent damage growth laws do not exist or are empirical. Finally, progressive damage analysis methods are currently a researcher's tool, and reliable, verified, user-friendly engineering tools are not yet available.

### **The State-of-the-Art in Composite Materials, Processes, and Manufacturing**

Significant improvements in the properties and processability of polymer matrix composite materials have occurred over the past 30 years. New epoxies have been developed to improve

significantly the toughness of composite materials. New thermosets and thermoplastics have been developed to increase significantly the use temperature of composite materials. Most epoxies cure at 350 F (177 C) and require an autoclave to insure proper fiber wetting, remove excess resin, minimize porosity, and promote the polymer cross-linking reaction. Material systems, such as T300/5208 with an intermediate modulus and intermediate strain-to-failure graphite fiber, were the first material to find extensive use in high-performance aerospace structure including the secondary structures and control surfaces for most commercial transport aircraft, the large payload bay doors of the NASA space shuttle orbiter vehicle, and the primary structure of the U.S. Air Force B-2 bomber. Higher performing material systems, such as the Toray T800H high-modulus, high-strain graphite fiber, and the toughened epoxy 3900-2 was used to manufacture the empennage structural components on the Boeing B-777. High performance military aircraft, such as the F-22, are manufactured out of materials systems such as IM7/5250-4, high-temperature bismaleimide (BMI thermoset) and high-modulus, high-strain graphite fibers. Recently, Boeing has introduced the newest transport aircraft, B787, into the worldwide fleet. This new aircraft has a number of unique structural design features enabled by composite materials. These innovative features include lower take-off weight, higher altitude flight for reduced drag, high cabin pressure for improved passenger comfort, and a novel wing tip design to reduce drag. The materials system used in the B-787 is the same material system used by Boeing in the B-777.

The aerospace industry structural requirements for high strength- and stiffness-to-weight ratios necessitate the use of large autoclaves and extensive part-unique tooling to align the fibers, consolidate the polymer, fully wet the fibers, and reduce voids and resin content in the cured matrix. The material layup step - the state of the art being large, robotic, tape laying machines - and the autoclave curing step in the manufacturing process are often choke-points that limits production rates. In recent years, the maturity of alternate composite fabrication processes, such as resin transfer molding (RTM), resin film infusion (RFI), and vacuum assisted resin transfer molding (VARTM) have led to increased use of textile preforms such as braided, woven, and knitted fiber preforms, and through-the-thickness stitching. These textile preforms have attractive features for low-cost manufacturing. Automated manufacturing methods such as high-speed fiber placement, powder-coated fiber tows, and textile preform and stitching machinery are becoming commonplace as replacements for the first generation, labor-intensive, manufacturing methods. The next generation manufacturing methods must be automated for high production rates and will likely be based on textile preforms and out-of-autoclave curing methods such as RTM, RFI, and VARTM. Finally, these automated methods are particularly suited to be integrated with an advanced high-fidelity modeling and simulation capability which will allow the rapid design and optimization of novel new products integrated with the manufacturing process tailored to each unique application, thus, dramatically speeding up the time from vehicle concept to the introduction of innovative new products into the marketplace.